APPLICATION OF BAKHTAR EMPIRICAL MODEL TO PERFORMANCE OPTIMIZATION OF UNDERGROUND MUNITIONS STORAGE STRUCTURES

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ABSTRACT

The hazardous effects associated with accidental detonation of munitions storage magazines is significantly reduced by storing explosives in chambers or magazines constructed below the ground surface. With the growth of population and encroachment of civilian neighborhoods onto military sites, the requirements for risk assessment and performance prediction of explosive storage magazines become more stringent. The market for this technology includes DOD and contractors laboratories in the United States and overseas and other organizations that store explosives. To meet the safety and the quantity-distance requirements, empirical and numerical models are needed for prediction of magazine performance for a given loading density. The method must account for the site-specific characteristics of the ground as well as those of the structural components. Innovative approaches are needed for *optimization of loading density, estimation of depth of cover*, and calculation of *pillar thickness between adjacent magazines* to prevent communication in case of accidental detonation in one chamber. The Bakhtar Empirical Models (BEM) for prediction of hazardous fragment range and quantity-distance around underground magazines were presented in the previous DDESB Seminar in 1996. In this paper, application of BEM to performance assessment of underground munitions storage structures is elaborated upon. Emphasis is directed towards optimization of loading density, estimation of depth of cover, and calculation of pillar thickness between adjacent magazines to render the facility non-responsive. Finally, a generalized approach for performance prediction of a non-responding underground magazine is discussed.

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INTRODUCTION

Hazard assessment associated with accidental detonation of an underground munitions storage magazine can be classified as:

- airblast (blast pressure);
- chemical hazards;
- thermal hazards;
- fragments (primary and secondary);
- ground shocks.

Extensive studies have been performed in the past on the hazardous effects of blast pressure, induced chemical and thermal environments, and ground shock. However, the degree and extent of the hazardous effects of blast-induced fragments from accidental detonation of underground munitions storage facilities still require additional research.. This can be attributed to the high cost associated with full scale testing of such facilities, in addition to difficulties associated with planning and coordination and environmental considerations.

The difficulties encountered with testing full-scale underground structures warrant the need for scale models in which the linear dimensions or geometry, of the prototype structure is reduced by a certain definite scale. In order to maintain dimensional heterogeneity between the model and prototype structure, the strength-related parameters also need to be scaled. The KLOTZ Tunnel explosion test conducted in China Lake, California (Halsey, et al., 1989) provided a unique opportunity for researchers to model the prototype event at a reduced scale under physical modeling at 1-g. Scaled model tests were conducted to model the KLOTZ Tunnels scenario. This included three tests by US Army (Joachim, 1998), five tests by US Air Force (Bakhtar, 1997), and several tests by the Norwegian Defense Construction Service (Jenssen, 1997).

The Air Force Tests were conducted by Bakhtar Associates (Bakhtar, 1997). For these tests not only the geometry but also the strength related parameters were scaled. Test results were subsequently used to formulate two empirical expressions for the prediction of maximum hazardous range of fragments and quantity-distance. The developed expressions, with the associated site characterization methodology, provide a unique technology for siting, design and construction, loading density optimization, performance assessment, and risk analysis of underground munitions storage structures. The applications of developed empirical expressions were successfully verified through four full-scale cases in the United States and Europe.

In this paper, the developed empirical criteria (Bakhtar, 1997) are used for performance optimization of an underground munitions storage magazine. The Steingletscher event, investigated by Bakhtar (1994), is the subject of the study. Bakhtar (1994) documents the overall characteristics of the geologic and engineered systems at the Steingletscher site

needed for this study. In addition, Kummer (1996) provided extensive documentation of this accident. The accident took place on November 2, 1992 and resulted in six fatalities. Rock cover was completely destroyed and induced fragments spread over a distance of a few hundred meters along the tunnel axis. Photographs presented in Figures 1 and 2 show the overall views of the site before and after the mishap.

CHARACTERIZATION OF GEOLOGIC SYSTEM

Index tests performed in the field provide the various parameters needed to define the geologic system. Application of the Q-System of rock mass characterization, developed by Barton et al., 1977, leads to the estimation of the upper and lower bounds for the overall modulus of deformability. P-Wave Velocity in the geologic system is measured by conducting a series of seismic reflection tests on the surface above the underground facility.

At the Steingletscher site, the geology appears to be magmitite (mixed rocks) type with homogeneous biotite schist, probably derived from basalt or gabro. The Swiss Military provided a document on the site geology, which was prepared by Schneider (1993). Table 1 shows the list of relevant rock properties.

Table 1. List of Rock Properties at the Steingletscher Accident Site(Schneider, 1993).

PARAMETER	RANGE	AVERAGE	REMARKS
$\sigma_{UNCONFINED}$	110 – 180 MPa	130 MPa	Perpendicular to schistosity
$\sigma_{UNCONFINED}$	80 – 140 MPa	120 MPa	Parallel to schistosity
MODULUS, E*	25×10^3 – 50×10^3 MPa	38×10^3 MPa	Perpendicular to schistosity
MODULUS, E*	20×10^3 – 35×10^3 MPa	30×10^3 MPa	Parallel to schistosity
TENSITE, T	6 – 15 MPa	10 MPa	Perpendicular to schistosity
TENSITE, T	3 – 10 MPa	7 MPa	Parallel to schistosity
$\phi°_{PEAK – DRY}$	27° - 40°	34°	----------------------
$\phi°_{RESIDUAL}$	25° - 38°	31°	---------------------
$C_{COHESION}$	1 – 2.5 MPa	1.8 MPa	----------------------
DENSITY, ρ	2.60 – 2.70 gm/cc	2.65 gm/cc	----------------------
JRC**	1 - 4	2	Based on Barton’s

* - values appear extremely high and represent those of intact samples
** - Joint Roughness Coefficient

Schmidt hammer tests were performed on several pieces of large debris which were retained at the bottom of the slope toe following the blast. With the hammer held horizontally, an average value of 42 was reported for the rebound height. After making the necessary correction for the hammer orientation, the unconfined compressive strength of the rock was estimated using Miller relationship given by Equation (1).

Figure 1 – Overall View of the Steingletscher Underground Munitions Storage Installation Before Accident.

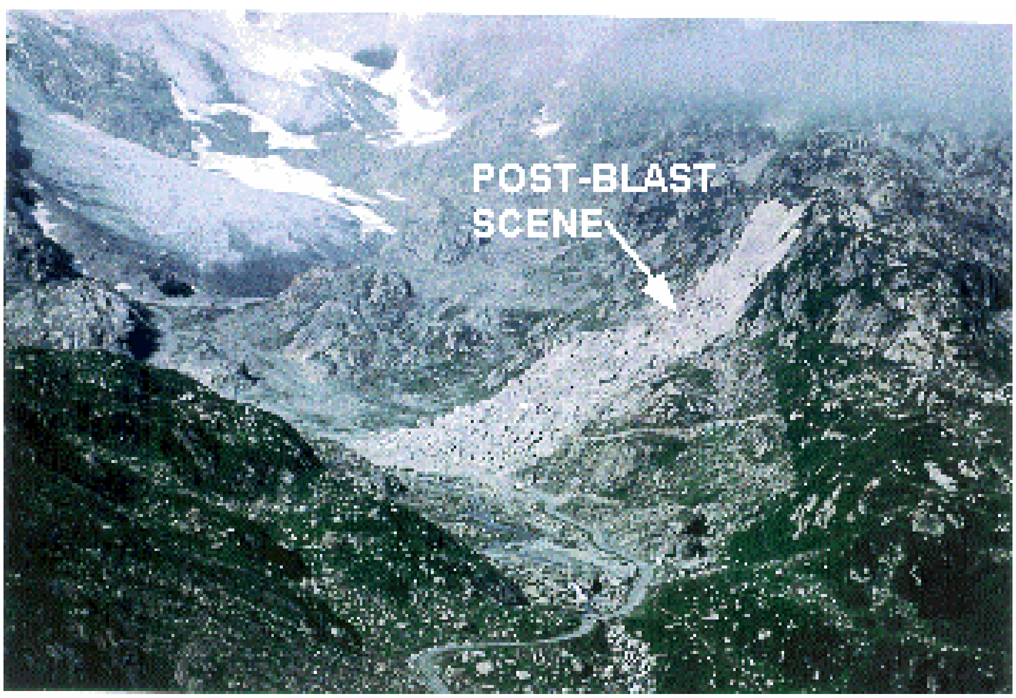

Figure 2 – Overall View of Steingletscher Underground Munitions Storage Facility After the Accident.

$$\log_{10}(\sigma_C) = 0.00088\ \gamma\ R\ + 1.01 \ldots \qquad (1)$$

Where:

σ_C = unconfined compressive strength of the surface (MN/m^2);
γ = unit weight of dry rock (kN/m^3);
R = rebound number.

The value for the average density of rock is provided in Table 1 as 2.65 gm/cc. The unit weight (γ) in kN/m^3 is determined as follows:

$$\gamma = 2.65 \times 1000 \times g \qquad \text{(Note: } g = 9.8146\ m/sec^2 \text{ in SI or Metric System)}$$
$$\gamma = 26{,}008.69\ N/m^3 \ = \ 26\ kN/m^3$$

Therefore, Equation (1) becomes

$$\log_{10}(\sigma_{UNCONFINED}) = 0.00088 \times 26 \times 42 + 1.01$$

or

$$\sigma_{UNCONFINED} = 94\ MPa \quad \text{(equivalent to 13,600 psi)}$$

The calculated value of the unconfined compressive strength using the Schmidt hammer is within the range reported by Schnider (1993) for intact rock samples. The average rebound of the Schmidt hammer was used to calculate the elastic modulus of the intact small rock samples. The modulus on the order of 45×10^3 MPa was obtained, and is within the range reported by Schnider (1993), in direction parallel to the schistosity of the rock.

The value of the elastic modulus obtained for the intact portion of rock samples using Schmidt hammer is reduced by a factor of “8” to account for scale effects resulting from the bedding planes and other geologic features observed in the rock mass. Scale effects in a rock mass has been discussed extensively by Barton et al., (1983), Bakhtar and Barton (1986) and many other researchers involved in rock mechanics. Its influence on the overall modulus of deformability and seismic wave velocity are well understood and universally accepted.

At the Steingletscher accident location, site inspection revealed evidence of bed separation at interfaces. In addition, fractures have been introduced into the geologic system post-event as a result of ground shock propagation. The bed separation can be attributed to the blast-induced stress waves (ground shock) reflecting at the free air interfaces, and acting as the tensile stress wave breaking and fracturing the geologic system (rock mass) under tension. Blast-induced fragments were observed along the toe of the slope to within few hundreds of meters from the original portal location, as can be seen in Figure 2. Recent experience by Bakhtar (1997) has shown that for fragment analysis of a massive internal explosion the orientation of the joints is not as critical as their spacing.

CHARACTERIZATION OF ENGINEERRED SYSTEM

For this analysis, the most important characteristics of the engineered system are cross sectional area of access tunnel (initial venting characteristics), total volume of storage chamber, and the overburden depth above the crown of the engineered system.

The partially steel and rock-bolt reinforced concrete lined "engineered system" at the Steingletscher consisted of two storage chambers, a truck loading and unloading ramp near the chambers, and a single entry access tunnel as shown in Figure 3.

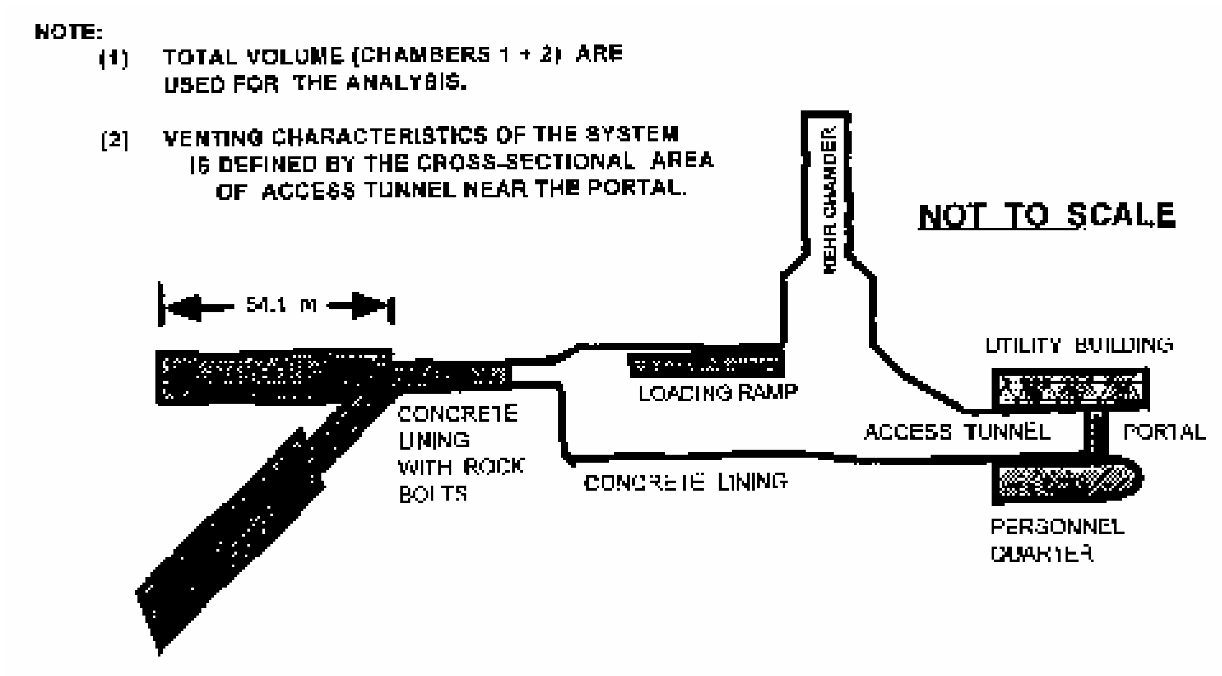

Figure 3 – Plan View of the Steingletscher Underground Munitions Storage Facility.

ANALYSIS

The Bakhtar Empirical Models (BEM) for prediction of hazardous fragment range and Quantity-Distance (Bakhtar, 1997) from detonation of underground munitions storage structures are given by Equations (2) and (3), respectively.

$$D_{NAX.\ RANGE} = 150\ [\ (R/C)^{-0.50}\ \ S^{0.87}\ \ g^{-0.25}\ ] \quad \ldots\ (2)$$

$$D_{QUANTITY\text{-}DISTANCE} = 90\ [\ (R/C)^{-0.22}\ \ S^{0.67}\ \ g^{-.011}\ ] \quad \ldots\ (3)$$

The various parameters in Equations (2) and (3) and their dimensional units are defined in Table 2.

Table 2 – Definitions for Parameters in Bakhtar Empirical Models (BEM), 1997.

PARAMETERS	DESCRIPTION	(UNITS) – DIMENSIONAL
$D_{MAX.\ RANGE}$	Max. Range of Hazardous Frag.	(m) L
$D_{Q\text{-}D}$	Quantity-Distance	(m) L
E	Equivalent Stiffness Characteristics - Geologic System	(MPa) F/A = $\{ML/L^2T^2\} = \{M/LT^2\}$
K	Loading Density {[explosive wt]/chamber vol]}	(kg/m^3) wt/vol = $ML/L^2T^3 = M/L^2T^2$
Z	Overburden thickness Above Chamber	(m) L
S	Initial Venting Characteristics of Engineered System	(m^2) L^2
V	P-Wave Velocity in Geologic System	(m/sec) L/T
G	Acceleration Due to Gravity	(m/sec^2) L/T2

Note: $g = 9.8146\ m/sec^2 = 32.2\ ft/\ sec^2$

The two terms denoted by "R" and "C" in Equations (2) and (3) are referred to as Dynamic Response Factor and Load Capacity Factor and defined as:

$$R = \frac{\text{EQUIVALENT MODULUS OF DEFORMABILITY}}{\text{SEISMIC WAVE VELOCITY}} = \frac{E}{V} \equiv \left\{ \frac{[\frac{M}{LT^2}]}{[\frac{L}{T}]} \right\} = [\frac{M}{L^2T}] \ldots\ldots.(4)$$

and

$$C = \frac{\text{CHAMBER LOADING DENSITY}}{\text{OVERBURDEN THICKNESS}} = \frac{K}{Z} \equiv [\frac{M}{L^3T^2}] \ldots \ldots\ldots\ldots\ldots. \ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

Using Equation 2, the site-specific data on the characteristics of the geologic and engineered systems were used to generate Loading Density-Fragment Range curve for the Steingletscher accident. For this example, the input data to Equation (2) is listed in Table 3. From the Loading Density-Fragment Range curve, Figure 4, the loading density corresponding to the maximum observed range of fragment (reported by the Swiss military Investigative team) is selected. This value is multiplied by the total volume of the chambers to determine the TNT equivalent weight of the explosive that caused the mishap.

The value obtained for the loading density can then be used in Equation (3) to calculate the quantity-distance (Q-D) based on the US DOD 6055.9 STD. The DOD standards define a hazardous fragment as one having an impact energy of 79 joules (58 ft-lb) or greater.

Table 3 – Input Parameters for Calculating Fragment Range and Quantity-Distance.

PARAMETERS	VALUES
Overall Modulus, E	5,500 MPa
Seismic Wave Velocity, v	3,000 m/sec – 2000 m/sec – 1000 m/sec
Total Chamber Volume, V	5,050 m^3
Overburden Depth, Z	51.5 m
Venting Characteristics, S	19.4 m^2
Initial Explosive Weight*	10 kg
k-factor	Counter set = 1.225

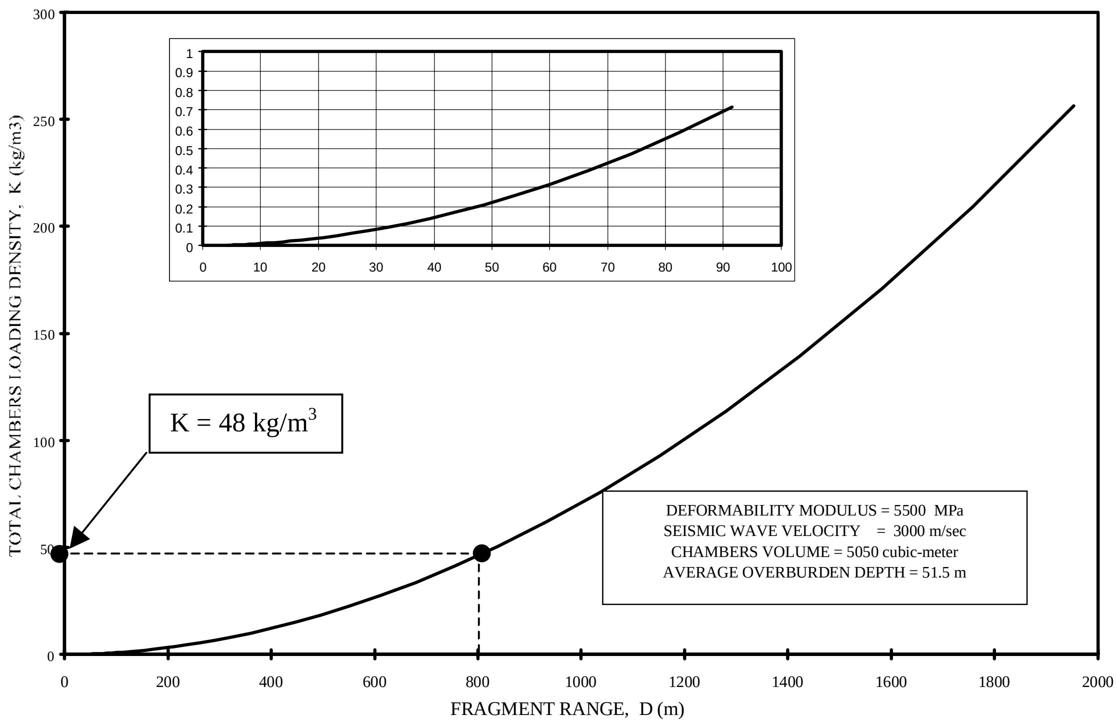

Figure 4 – Variations of Loading Density with Fragment Range for Steingletscher Accident Reported By Bakhtar and Jenus (1994).

The maximum hazardous fragment range reported by the Swiss investigators (Kummer, 1996) is 800 m. The dotted line in Figure 4 shows the loading density corresponding to the 800 m fragment range on the characteristics curve is 48 kg/m^3. Total volume of the explosive storage chambers is given in Table 3 as 5050 m^3. Therefore, the TNT equivalent weight of the explosive that caused the mishap is calculated to be 243 tons.

The explosive weight is substituted in Equation (4) to calculate the Q-D, based on the US DOD standards, for this installation. This results in a quantity distance of 440 m. These values are in very close agreement (10% or better) with those reported by the Swiss investigators (Kummer, 1996).

The scope of the analysis was extended to find out what should have been the average depth of cover for the Steingletscher installation to reduce the Q-D by 10%, assuming that the overall characteristics of the geologic and engineered systems stayed the same.

Substituting C from Equation (5) into Equation (3) and solving for Z with Quantity-Distance reduced to 396 m, we get:

$$396 = 90\{ [5500/3000] / [48/Z] \}^{-0.22}\ 19.4^{0.67}\ \ 9.8146^{-0.11} \longrightarrow Z = 83 \text{ m}$$

This indicates that, assuming all the other parameters (including the loading density) are the same, an additional 23-m of cover is needed to reduce the quantity-distance by 10%.

REAMRKS

The approach presented above can be used for optimization of loading density in an underground munitions storage magazine. It is extremely important to use site specific data on characteristics of the geologic and engineered systems. Typical data available in the literature on a rock mass does not necessarily represent the local characteristics and should not be used for such analysis. A good example is the geologic system hosting the KLOTZ Tunnel in Älvdalen, Sweden. At this site, the geology consisted mainly of intrusive igneous rocks. The underground facility was constructed in a heavily fractured granitic rock mass, as can be seen in Figure 5.

The main body of rock appears to have granodiorite and diorite composition. For this kind of igneous rock, typical data in the literature (Jumikis, 1982) gives the range for the modulus of deformability (elastic modulus) between 25 GPa (3.6 x 10^6 psi) to 68 GPa (9.8 x 10^6 psi). The site characterization tests (Bakhtar and Jenus, 1994) resulted in a range of values for the modulus of deformability to be determined between 1.66 GPa (0.24 x 10^6 psi) to 0.42 GPa (0.06 x 10^6 psi). The large discrepancy can be attributed to the scale effects in the geologic system. In addition, at the Älvdalen tunnel, extremely disturbed zones observed within the geologic and engineered systems are attributable to the several explosion tests conducted within the Chambers A and B since 1986. Furthermore, the results of rock mass and joint characterization define the disturbed hydraulic and mechanical characteristics of the geologic system. These characteristics provide important site-specific data, which can be used to determine the extent and magnitude of “ground shocks” using hydrocodes, and to establish a safe zone on the surface for inhabited buildings.

Index testing and application of the Q-system of rock mass characterization, developed by Barton, et al., 1977, uniquely provide the required data on geologic system for rock mass and joint characterization.

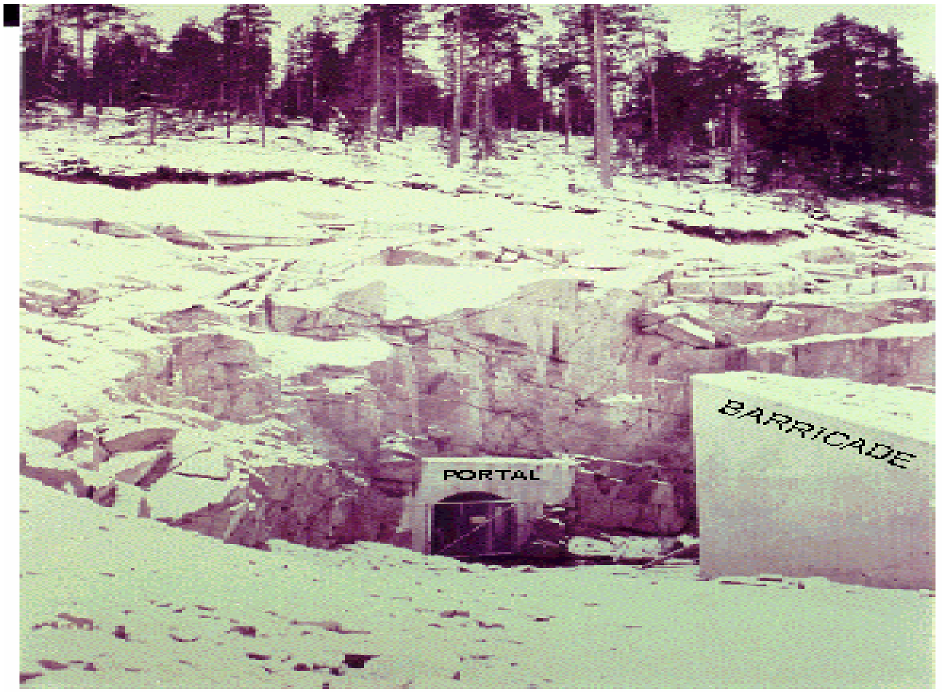

Figure 5 - KLOTZ Tunnel in Älvdalen, Sweden. Note the horizontal scale is stretched in this photograph.

SEPARATION DISTANCE BETWEEN UNDERGROUND MAGAZINES

By and large, underground facilities for storage of munitions are constructed at shallow depths. For multi-chamber installations, calculation of the pillar thickness should be made by taking into the account the overall characteristics of the roof rock. For large chambers, the deformation and strength properties of the roof rock are the most important properties. Application of the Q-system of rock mass characterization allows the upper and lower bonds of the overall modulus of deformability to be determined. This data can be used for numerical modeling (parametric studies) stability analysis as well as the design and construction of the facility.

If the chambers are to be on the same elevation, there are a number of ways to calculate average pillar stress in a complex underground facility. These include tributary area, beam deflection, pillar deflection and load carrying (foundation) coefficient. The beam and pillar deflection methods assume linear elastic behavior and the overburden loading conditions are usually approximated as a thick beam or plate. This method of analysis is commonly practiced in mining industry. However, for the munitions storage facility, in addition to the long-term pillar stability requirement, there are also safety requirements. These

requirements stipulate that an accidental detonation in one chamber should not cause sympathetic detonation in the adjacent magazines. Therefore, a thickness of pillar should be used that will prevent magazine communication in case of an accidental detonation.

In a case of an accidental detonation in an underground magazine, even if the cover does not break, the induced ground shock (blast-induced stress waves) cause localized damage to the engineered and host geologic systems. The extent and degree of the damage depends on the amount of explosive detonated, magazine depth and construction, and site specific geologic conditions. For adjacent magazines, the induced ground shock from one magazine may not cause sympathetic detonation in the other (Brown, 1998). However, crushing caused by violent impact of the stored munitions resulting from pillar failure may cause the sympathetic detonation in the neighboring magazine. The pillar design should account for such mishaps.

Because of difficulties and high costs associated with testing full scale underground structures, the physical modeling at 1-g approach may provide the most cost-effective technique for performance evaluation of such structures. Furthermore, if the similitude requirements are followed, the results obtained are real and can be applied for the design and construction of the underground facility. Furthermore, rotation of the principal axis may enable the BEM represented by Equations (2) and (3) to work for calculation of pillar thickness between adjacent magazines. However, its validation would require additional scaled model tests.

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